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Comprehensive Comparison of PWM and SVM based Three Phase AC to AC Matrix Converters

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Abstract

Converters are employed in wide range of applications to save energy and attain desirable voltage. Matrix converter can convert three phase AC input to three phase AC output with variable voltage amplitude and frequency directly. It can be used as a bidirectional power flow converter without any intermediate storage element. The objective of this proposed research is to minimize the harmonic losses to get maximum output voltage ratio, sinusoidal current, desired variable voltage amplitude and desired variable frequency. Pulse width modulation and space vector modulation algorithm control the input and output voltage and frequency independently. In this research work, pulse width modulation and space vector modulation based matrix converters will be designed to attain voltage ratio up to 1 and to reduce switching losses so that total harmonic distortion could be minimized with sinusoidal waveforms of desired amplitude and frequency. Comparisons will be drawn on the basis of harmonic contents present in the desired output waveform by changing the characteristics of input waveform. Simulation environment will be created in Matlab. [1]

Keywords: *Pulse Width Modulation, Space Vector Modulation, Matrix Converters, Matlab*

Nomenclature

PWM	Pulse Width Modulation
SVM	Space Vector Modulation
AC	Alternating Current
DC	Direct Current
BJT	Bipolar Junction Transistor
MOSFET	Metal Oxide Silicon Field Effect Transistor
IGBT	Insulated Gate Bipolar Junction Transistor

[1]This study has been implemented at Department of Electrical Engineering, University of Lahore, Pakistan

1 Introduction

The basic component of matrix converter is bidirectional switch which are forcibly commutated. Switches are used in controlled manner to generate a variable frequency output. There is no dc link between two different voltage sources and also there is no need of using energy storing active elements link capacitor. The switches are used in controlled way due to which the operation at high frequency is possible. There are many type of matrix converters in which the components used can be reduced according to the requirement and thus the modulation technique is also less complex [22, 9, 20, 18, 15].

Pulses of variable widths are generated using pulse width modulation that represent the amplitude of an analogue signal. The main use of pulse width modulation is that the power supplied to the electrical loads especially of rotating loads like motors which have some inertia, can be controlled. Thus, motors can be made to operate at variable speed by using pulse width modulation.

To control the pulse width modulation, another algorithm space vector pulse width modulation is employed [19].It is used to drive a motor at variable speed by generating three phase alternating currents waveform. There are many methods and variations of space vector pulse width modulation, each having different quality and different requirement of computation. Due to rapid switching actions, the harmonics are generated. The elimination of these harmonics is one of the basic purposes of using space vector pulse width modulation [30].

Non linear loads generate current harmonics and voltage harmonics in a system. High order frequencies are major cause of problems in quality of power supplied. Harmonics result in increased heating of the equipments. It is highly desirable to reduce the harmonics in any power system. Low order harmonics which are undesirable, can be eliminated by selecting most preferable harmonics elimination technique [21, 24]. The operation of electrical system is highly

effected due to generation of harmonics. A lot of attention in any system is paid to the reduction of harmonics [11, 27]. The operations of a systems have standards to maintain and to limit up to which harmonics can be added to the system [1, 2, 3]. By using multiple winding transformer in multiple connection at input side of a system, current harmonics can be reduced. Harmonics can also be removed using different active and passive filter topologies [5, 28, 4].

The matrix converter topologies are more attractive after the development of power switches like bipolar junction transistors (BJTs), metal oxide silicon field effect transistors (MOSFETs) and insulated gate bipolar junction transistors (IGBTs) [12]. The first time development of matrix converter was in 1980 [31, 32]. Venturini and Alesia in 1980, presented the converter using bidirectional switches and they introduced the name of matrix converter for the first time. The modulation technique introduced by them is known as direct transfer function approach. In order to obtain the desired output voltages, the input voltages are multiplied by the modulation matrix [23] [8].

After them in 1983, Rodriguez introduced a different technique for matrix converter operation introducing fictitious DC link [29]. According to his technique, the output was switched between the most positive input line and the most negative input line. This technique is known as indirect transfer function approach [26].

The method for the control of Matrix Converters was introduced by Braun in 1983 [6] and by Kastner and Rodriguez in 1985 [14]. The first paper to provide the solution of modulation scheme in matrix converters using space modulation was published in 1989 by Huber [10]. Schauder and Neft proved this fact experimentally in 1992 that high quality of input current and output current can be obtained by using matrix converter which comprises of only bidirectional switches [25]. The switching should be performed in such a manner that there should be no high spikes of voltages and current which can damage the switches made up of semi-conductor materials. This fact affected the interests of using matrix converters. This issue has been solved due to the development of microprocessors based controllers and multistage switching and commutation techniques.

Implementation and operation of bidirectional switches [17, 7] under normal condition with active filters [16, 33] are main themes of researches. Lanka Parampil, Ushakomari and Nisha removed the harmonics in three phase inverters using space vector pulse width modulation [13].

In this research work, three phase input and three phase output will be compared and modulated according to requirement by a modulation block. The modulated voltages will be fed to a matrix converter which comprises IGBTs whose operation will be controlled by applying a PWM and SVM at the gates of the IGBTs. The output from the matrix converter will be fed to different loads like synchronous motor, induction motor, resistive load and RL load whose harmonics will be removed.

The remainder of the paper is organized as follows: Section II focuses on description and mathematical framework of matrix converter, pulse width modulation and space vector modulation Section III emphasizes on mathematical formulation of modulation techniques. Section IV covers the simulation results and Matlab/Simulink models. This research work and its simulation results are concluded in section V.

2 Mathematical Formulation of Research Problem

2.1 Matrix Converter

A device that changes the frequency of input supply is called matrix converter. The basic components of matrix converter is bidirectional switches which allows any output phase to be connected to any of the three input phase for a given length of line and any desired frequency can be generated. The main advantages of the matrix converter are as follow:

- It eliminates the need of large reactive components which are used in AC-DC-AC type inverters.
- The use of bidirectional switches allows the energy to be regenerated back to the supply or grid.
- This allows the input current waveforms to be sinusoidal and suitable switching can be provided the unity input power factor.
- Due to absence of large reactive elements like capacitors and inductors, the size is small.
- Matrix converter provides more power to weight ratio.
- DC link in back to back inverters is absent.
- The number of switches used are also less.

2.2 Different Types of Matrix Converters

2.2.1 AC-DC-AC Converters

These types of converters are known as dc-link converters. There are two types of dc-link converters, which are voltage source inverters and current source inverters. In voltage source inverters, the rectifier stage is realized using diodes bridge while the dc link circuit consists of a shunt capacitor. In current source

inverter the rectifier stage is realized using phase controlled switching bridge and he dc link circuit consists of serried inductor. An AC-DC-AC converter with bidirectional power flow can be realized using pwm rectifier and then a pwm inverter to the dc link. Energy storing element that is common to both sides forms the dc-link between them.

2.2.2 Cyclo-Converters

There is no dc link in cyclo-converters. The cyclo-converter generates the output of variable frequency. The output generated is almost sinusoidal because the segments of the input waveform are transferred to the output side by switching. SCRâĂŹs are usually used in cyclo-converters. The output frequency of the cyclo-converter can never be greater than the input frequency.

2.2.3 Matrix Converter

Matrix Converter converts directly AC to AC without using any dc link. This increases reliability and stability of the system. Bidirectional switches using IGBTâĂŹs are used commonly in matrix converters. Depending on the number and types of components used, the matrix converters are further classified into many types.

a. Sparse Matrix Converter
In this type of matrix converter, the numbers of required switches are less, so the complexity of the gate drive circuit is reduced. The function is identical to direct matrix converter. 18 diodes and 15 switches are required for the sparse type matrix converter.

b. Very Sparse Matrix Converter
In this type, the number and diodes are increased and correspondingly the number of switches is reduced as compared to the sparse matrix converter. Though gate drive complexity is reduced but due to increase in the number of diodes, the conduction losses are increased.

c. Ultra Sparse Matrix Converter
Only unidirectional switches are used in the input stage of ultra sparse matrix converter. So, these types of matrix converters are used for the variable speed drives which are of low dynamics. The topology of ultra sparse matrix converter introduces phase displacement between input voltages and input currents. Only 12 diodes and 9 switching devices are required for this type of matrix converter.

d. Hybrid Matrix Converters
The hybrid matrix converter converts AC/DC/AC but does not use any dc link or reactive elements like capacitor or inductor. The hybrid matrix converters are further classified into two types depending on their operation. If hybrid matrix converter converts both voltage and current commutation in same stage then this is called hybrid direct matrix converters. If current and voltages are converted in different steps then these are called hybrid indirect matrix converter.

2.3 Basics of Matrix Converter:

The matrix converter is direct AC-AC converter for converting one frequency AC supply to another frequency AC supply without involving an intermediate DC link capacitor.

It has a three phase input supply. The three phase output voltages obtained are V_a, V_b and V_c. There are nine bidirectional switches from S_{11} to S_{33} which represent a nine matrix components mathematically.

The three phase matrix converter converts the three phase input of given amplitude (V_i) and frequency (f_i) to three phase output of a fixed amplitude (V_o) and frequency (f_o). Any desirable output frequency can be achieved by this converter. The three phase input voltages of the converter and required out put voltages are given by (1) and (2).

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = V_i \begin{bmatrix} \cos(\omega_i t) \\ \cos(\omega_i t + \frac{2\pi}{3}) \\ \cos(\omega_i t + \frac{4\pi}{3}) \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = V_0 \begin{bmatrix} \cos(\omega_i t) \\ \cos(\omega_i t + \frac{2\pi}{3}) \\ \cos(\omega_i t + \frac{4\pi}{3}) \end{bmatrix} \tag{2}$$

The input and output voltage are related to each other according to the following matrix equations as shown in (3). Here M_{ij} is the duty cycle of switch S_{11} and so on.

$$\begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix} \begin{bmatrix} V_A(t) \\ V_B(t) \\ V_C(t) \end{bmatrix} \tag{3}$$

Normally, the Matrix Converter is fed by a voltage source and switching should be performed in such a way that none of the input terminals are short circuited. The matrix converter applications are mostly used to drive inductive loads, so the the switching should also be performed such that the output phase is never open circuit because it will cause discontinuous supply to load and also the inductive kicks will be caused. The load and source voltages and input and output currents can be expressed as vectors defined by (4) and (5).

$$v_o = \begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} ; V_i = \begin{bmatrix} V_A(t) \\ V_B(t) \\ V_C(t) \end{bmatrix} \tag{4}$$

$$i_o = \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} ; i_i = \begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix} \tag{5}$$

2.4 Pulse Width Modulation

Pulse width modulation is a technique in which a message or a signal is encoded in such a way that it takes

the form of a pulsating signal. This technique is used to encode any information that can be used for transmission. One of the main use of PWM is the control of power that can be supplied to the load. By constantly turning on and off the switching device between load and the source, the value of voltage required is achieved. This phenomenon is carried out at high switching frequency. By varying the duty cycle of the PWM signal, the amount of power supplied to the load is varied. Due to constantly on and off the switching device the desired output waveform will not be smooth. So, in order to keep the output waveform smooth, the switching frequency should be as high as possible.

The switching frequency of a PWM signal is very high which enables the power electronic switching devices to be saturated hardly. So, between on and off state of the switching the transition interval is very short and hence, switching losses are also less. During off state of a controlled switch, the is no flow of current and during on state, the forward voltage drop is almost zero. So, using PWM signal for switching the switching losses are almost zero.

Depending on the requirement, width of the pulse is modulated. The term duty cycle is defined as the ratio of on time of signal to the total time period of the signal as given by (6):

$$\text{Duty Cycle (D)} = t_{on}/t_{on} + t_{off} \tag{6}$$

Duty cycle is represented in percentage like 50%, means on for half of the time and off for half of the time, 100% duty cycle defines fully on.

The steady state operation of a dc to dc type converter is made possible when the reference signal used for PWM generation is constant and does not vary. In dc to dc converters, the reference is assumed to be a dc value. In AC to DC or DC to AC type converters, the reference is assumed to contain the fundamental frequency component of desired output frequency. Similarly in case of multiple or 3 phase converters, the sinusoidal reference signals are shifted by desired amount of phase shift as required in the output voltages. In three phase inverters, the reference signals are shifted by zero degree, 120 degrees and 240 degrees to generate the desired switching. In the generation of switching sequences, reference signals may also contain harmonics mostly 3rd harmonics which are self introduced so that utilization of dc voltages can be increased.

2.4.1 Modulation algorithm for PWM based Matrix Converter

Assuming that the switches are ideal, i.e., no losses occurs in switches. The three phase input supply is given by (7).

$$\begin{pmatrix} V_A(t) \\ V_B(t) \\ V_C(t) \end{pmatrix} = \begin{pmatrix} cos(\omega_i t) \\ cos(\omega_i t + \frac{2\pi}{3}) \\ cos(\omega_i t + \frac{4\pi}{3}) \end{pmatrix} \times V_{im} \tag{7}$$

The switching is performed after a sequence of time. This time T_s which is reciprocal to the switching frequency f_s. The switching time in term of switches shown is defined in (8)

$$\begin{aligned} T_s &= t_{Aa} + t_{Ba} + t_{Ca} \\ &= t_{Ab} + t_{Bb} + t_{Cb} \\ &= t_{Ac} + t_{Bc} + t_{Cc} \\ &= \frac{1}{f_s} \end{aligned} \tag{8}$$

The switching frequency f_s is constant which means that the length of each sequence is same. The values that are to be received at the output side is say $V_a(t), V_b(t)$ and $V_c(t)$ which should be displaced from each other by 120 degrees. The three phase output voltages in terms of switching time are given by (9) (10) and (11)

$$\begin{aligned} V_a(t) &= V_{im}cos(\omega t)\frac{t_{Aa}}{T_s} + V_{im}cos(\omega t + \frac{2\pi}{3})\frac{t_{Ba}}{T_s} \\ &+ cos(\omega t + \frac{4\pi}{3})\frac{t_{Ca}}{T_s} \end{aligned} \tag{9}$$

$$\begin{aligned} V_b(t) &= V_{im}cos(\omega t)\frac{t_{Ab}}{T_s} + V_{im}cos(\omega t + \frac{2\pi}{3})\frac{t_{Bb}}{T_s} \\ &+ cos(\omega t + \frac{4\pi}{3})\frac{t_{Cb}}{T_s} \end{aligned} \tag{10}$$

$$\begin{aligned} V_c(t) &= V_{im}cos(\omega t)\frac{t_{Ac}}{T_s} + V_{im}cos(\omega t + \frac{2\pi}{3})\frac{t_{Bc}}{T_s} \\ &+ cos(\omega t + \frac{4\pi}{3})\frac{t_{Cc}}{T_s} \end{aligned} \tag{11}$$

Now, if the input frequency is increased from ω_i to ω_o then a modulating frequency ω_m has to be added in the input frequency given by (12).

$$\omega_o = \omega_i + \omega_m \tag{12}$$

The output voltage $V_a(t)$ has zero degree shift in its phase and switches t_{Aa}, t_{Ba} and t_{Ca} determine the $V_a(t)$ by connecting to first, second and third phase respectively. Thus to maintain zero degree shift in phase $V_a(t)$, the switching sequence t_{Ba} and t_{Ca} should be retarded by 120 degrees and 240 degrees respectively. And same is for other two phases. The switching sequences thus formed are given by (13) (14) (15) (16) (17) (18) (19) (20) and (21).

V_o at 0^o

$$t_{Aa} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta)) \tag{13}$$

$$t_{Ba} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta - \frac{2\pi}{3})) \tag{14}$$

$$t_{Ca} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta - \frac{4\pi}{3})) \tag{15}$$

V_o at 120^o

$$t_{Ab} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta - \frac{4\pi}{3})) \tag{16}$$

$$t_{Bb} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta)) \tag{17}$$

$$t_{Cb} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta - \frac{2\pi}{3})) \tag{18}$$

V_o at 240^o

$$t_{Ac} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta - \frac{2\pi}{3})) \tag{19}$$

$$t_{Bc} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta - \frac{4\pi}{3})) \tag{20}$$

$$t_{Cc} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta)) \tag{21}$$

If these values of the time sequence of each switch is substituted in the equation of the desired output voltages as defined before, then the modulation matrix is given by (22).

$$M(t) = \tfrac{1}{3}\begin{bmatrix}1 & 1 & 1\\ 1 & 1 & 1\\ 1 & 1 & 1\end{bmatrix} + \tfrac{2q}{3}$$
$$\begin{bmatrix} cos(\omega_m t) & cos(\omega_m t - \frac{2\pi}{3}) & cos(\omega_m t - \frac{4\pi}{3}) \\ cos(\omega_m t - \frac{4\pi}{3}) & cos(\omega_m t) & cos(\omega_m t - \frac{2\pi}{3}) \\ cos(\omega_m t - \frac{2\pi}{3}) & cos(\omega_m t - \frac{4\pi}{3}) & cos(\omega_m t \end{bmatrix} \tag{22}$$

with $\omega_m = (\omega_0 - \omega_i)$. The output and input voltages are related to each other with the help of modulation matrix as given in (23).

$$V_o(t) = M(t).V_i(t) \tag{23}$$

So the output voltages are given by (24).

$$V(t) = \frac{1}{3}\begin{bmatrix}1 & 1 & 1\\ 1 & 1 & 1\\ 1 & 1 & 1\end{bmatrix} + \tfrac{2q}{3}$$
$$\begin{bmatrix} cos(\omega_m t) & cos(\omega_m t - \frac{2\pi}{3}) & cos(\omega_m t - \frac{4\pi}{3}) \\ cos(\omega_m t - \frac{4\pi}{3}) & cos(\omega_m t) & cos(\omega_m t - \frac{2\pi}{3}) \\ cos(\omega_m t - \frac{2\pi}{3}) & cos(\omega_m t - \frac{4\pi}{3})) & cos(\omega_m t) \end{bmatrix}$$
$$\times \begin{bmatrix} V_m(\omega_m t) \\ V_m(\omega_m t - \frac{2\pi}{3}) \\ V_m(\omega_m t - \frac{2\pi}{3}) \end{bmatrix} \tag{24}$$

2.5 Space Vector Modulation

The generated three phase voltages vary from each other by 120 degrees with the frequency same as of reference signal. The reference signal can be varied by varying the time period T_s as $T_s = 1/f_s$, where f_s is switching frequency. The reference signal can be generated from a three phase using $d - q$ or $\alpha - \beta - \gamma$ transformation. Various combinations exist for selecting the switching sequence of switches but each strategy has its own switching losses as shown in figure 1.

Vector	A+	B+	C+	A-	B-	C-
$V_0 = (000)$	OFF	OFF	OFF	ON	ON	ON
$V_1 = (100)$	ON	OFF	OFF	OFF	ON	ON
$V_2 = (110)$	ON	ON	OFF	OFF	OFF	ON
$V_3 = (010)$	OFF	ON	OFF	ON	OFF	ON
$V_4 = (011)$	OFF	ON	ON	ON	OFF	OFF
$V_5 = (001)$	OFF	OFF	ON	ON	ON	OFF
$V_6 = (101)$	ON	OFF	ON	OFF	ON	OFF
$V_7 = (111)$	ON	ON	ON	OFF	OFF	OFF

V_{AB}	V_{BC}	V_{CA}	*state*
0	0	0	Zero
$+V_{dc}$	0	$-V_{dc}$	Active
0	$+V_{dc}$	$-V_{dc}$	Active
$-V_{dc}$	$+V_{dc}$	0	Active
$-V_{dc}$	0	$+V_{dc}$	Active
0	$-V_{dc}$	$+V_{dc}$	Active
$+V_{dc}$	$-V_{dc}$	0	Active
0	0	0	Zero

Figure 1: This table shows combination of switching sequence.

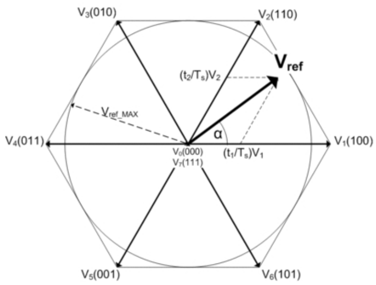

Figure 2: Vector representation of SVM signal

Two zero vectors and six active vectors can be represented in the form of a hexagon in such a way that the length of each vector represents the magnitude of voltages as showm in figure 2. The rotation of vectors represents the angular speed of the system. As previous discussed for balanced loads, space vectors are represented in 2-Dimensional figure. To minimize the time taken during toggling of states and to maintain the effective frequency of the switches used at minimum, the SVM topology prefers switching between two nearest active states. Using this approach, in every step only one leg is affected. Using proper switching, the effective output voltage to input voltage ratio can be increased to more than 90.6%.

The six active vectors can be represented by (25).

$$V_k = \frac{2}{3}V_d e^{j(k-1)\frac{\pi}{3}} \text{with } k = (1, 2....6) \tag{25}$$

SVM vectors are represented graphically by equally dividing six sectors of a hexagon. The switching of only one inverter leg provides minimum switching frequency and optimum harmonic performance. Using, SVM we can define any reference vector as a combination of two active vectors at any instant of time. Suppose that in figure 2, V_{ref} shown is in k sector and the active vectors adjacent to V_{ref} are V_k and V_{k+1}. So, the reduced equation is given by (26).

$$V_{ref}.\frac{T_s}{2} = V_k.T_k + V_{k+1}.T_{k+1} \tag{26}$$

Where T_s is switching period. If this equation is split in real and imaginary parts,then it is given by (27) and (28).

$$\begin{bmatrix} V_{alpha} \\ V_{beta} \end{bmatrix} * \frac{T_s}{2} = \frac{2}{3} V_d T_k \begin{bmatrix} cos\frac{(k-1)*pi}{3} \\ sin\frac{(k-1)*pi}{3} \end{bmatrix} + \frac{2}{3} V_d T_{k+1} \begin{bmatrix} cos\frac{(k)*pi}{3} \\ sin\frac{(k)*pi}{3} \end{bmatrix} \tag{27}$$

$$\begin{bmatrix} V_{alpha} \\ V_{beta} \end{bmatrix} * \frac{T_s}{2} = \frac{2}{3} V_d \begin{bmatrix} cos\frac{(k-1)*pi}{3} & cos\frac{(k)*pi}{3} \\ sin\frac{(k-1)*pi}{3} & cos\frac{(k)*pi}{3} \end{bmatrix} \begin{bmatrix} T_k \\ T_{k+1} \end{bmatrix} \tag{28}$$

k is determined by taking the argument of the reference vector given by (29).

$$\frac{(k-1)*pi}{3} \le arg \begin{bmatrix} V_a \\ V_b \end{bmatrix} \le \frac{k*pi}{3} \tag{29}$$

V_{ref} makes a circular path of radius V_{ref} at an angular velocity in the complex plane. So, larger the radius of the trajectory circle, largest is the magnitude of voltage that can be achieved. This circle is tangential to the mid points of the lines connecting the ends of the active state vectors.The maximum achievable phase voltages are given by (30).

$$|V_{ref|_{max}} = \frac{2}{3} V_d \frac{\sqrt{3}}{2} = \frac{1}{\sqrt{3}} V_d \tag{30}$$

Following the definition of modulation index introduced in above, the corresponding maximum modulation index is given by (31).

$$m_{max\,cont} = \frac{|V_{ref}|_{max}}{V_{max,sixstep}} = \frac{\frac{1}{\sqrt{3}}.V_d}{\frac{2}{\pi}.V_d} = \frac{\pi}{2\sqrt{3}} = 0.906 \tag{31}$$

With the definition of modulation index the computation of the inverter switching times does not require the knowledge of the adopted DC-link voltage but depends only on the desired modulation index. Only space vector topology provides the best suitable switching sequence according to the type of loads like pulsating load, non-linear load and static load etc. The advantages of SVM are:

- THD of the output voltage is low
- DC bus utilization in case of SVM is at least 15% more than the PWM technique used
- SVM offers low peak currents in controlled switches as compared to PWM.
- Higher performance, efficiency and reliability is achieved using SVM as compared to PWM based inverters of similar type.

Switching Configuration List	Switches	Switches	ON	V_o	a_o	i_i	b_h
+1	S_{11}	S_{22}	S_{33}	$\frac{2}{3}V_{12i}$	0	$\frac{2}{\sqrt{3}}i_{01}$	$\frac{-\pi}{6}$
-1	S_{12}	S_{21}	S_{31}	$\frac{-2}{3}V_{12i}$	0	$\frac{-2}{\sqrt{3}}i_{01}$	$\frac{-\pi}{6}$
+2	S_{12}	S_{23}	S_{33}	$\frac{2}{3}V_{23i}$	0	$\frac{2}{\sqrt{3}}i_{01}$	$\frac{\pi}{2}$
-2	S_{13}	S_{22}	S_{32}	$\frac{-2}{3}V_{23i}$	0	$\frac{-2}{\sqrt{3}}i_{01}$	$\frac{\pi}{2}$
+3	S_{13}	S_{21}	S_{31}	$\frac{2}{3}V_{31i}$	0	$\frac{2}{\sqrt{3}}i_{01}$	$\frac{7\pi}{6}$
-3	S_{11}	S_{23}	S_{33}	$\frac{-2}{3}V_{12i}$	0	$\frac{-2}{\sqrt{3}}i_{01}$	$\frac{7\pi}{6}$
-3	S_{11}	S_{23}	S_{33}	$\frac{-2}{3}V_{12i}$	0	$\frac{-2}{\sqrt{3}}i_{01}$	$\frac{7\pi}{6}$
+4	S_{12}	S_{21}	S_{32}	$\frac{2}{3}V_{12i}$	$\frac{2\pi}{3}$	$\frac{2}{\sqrt{3}}i_{02}$	$\frac{-\pi}{6}$
-4	S_{11}	S_{22}	S_{31}	$\frac{-2}{3}V_{12i}$	$\frac{2\pi}{3}$	$\frac{-2}{\sqrt{3}}i_{02}$	$\frac{-\pi}{6}$
+5	S_{13}	S_{22}	S_{33}	$\frac{2}{3}V_{23i}$	$\frac{2\pi}{3}$	$\frac{2}{\sqrt{3}}i_{02}$	$\frac{\pi}{2}$
-5	S_{12}	S_{23}	S_{32}	$\frac{-2}{3}V_{23i}$	$\frac{2\pi}{3}$	$\frac{-2}{\sqrt{3}}i_{02}$	$\frac{\pi}{2}$
+6	S_{11}	S_{23}	S_{31}	$\frac{2}{3}V_{31i}$	$\frac{2\pi}{3}$	$\frac{2}{\sqrt{3}}i_{02}$	$\frac{7\pi}{6}$
-6	S_{13}	S_{21}	S_{33}	$\frac{-2}{3}V_{31i}$	$\frac{2\pi}{3}$	$\frac{-2}{\sqrt{3}}i_{02}$	$\frac{7\pi}{6}$
+7	S_{12}	S_{22}	S_{31}	$\frac{-2}{3}V_{12i}$	$\frac{4\pi}{3}$	$\frac{2}{\sqrt{3}}i_{03}$	$\frac{-\pi}{6}$
-7	S_{11}	S_{21}	S_{32}	$\frac{-2}{3}V_{12i}$	$\frac{4\pi}{3}$	$\frac{-2}{\sqrt{3}}i_{03}$	$\frac{-\pi}{6}$
+8	S_{13}	S_{23}	S_{32}	$\frac{2}{3}V_{23i}$	$\frac{4\pi}{3}$	$\frac{2}{\sqrt{3}}i_{03}$	$\frac{\pi}{2}$
-8	S_{12}	S_{22}	S_{33}	$\frac{-2}{3}V_{23i}$	$\frac{4\pi}{3}$	$\frac{-2}{\sqrt{3}}i_{03}$	$\frac{\pi}{2}$
+9	S_{11}	S_{21}	S_{33}	$\frac{2}{3}V_{31i}$	$\frac{4\pi}{3}$	$\frac{2}{\sqrt{3}}i_{03}$	$\frac{7\pi}{6}$
-9	S_{13}	S_{23}	S_{31}	$\frac{2}{3}V_{31i}$	$\frac{4\pi}{3}$	$\frac{-2}{\sqrt{3}}i_{03}$	$\frac{7\pi}{6}$
0_1	S_{11}	S_{21}	S_{31}	0	–	0	–
0_2	S_{12}	S_{22}	S_{32}	0	–	0	–
0_3	S_{13}	S_{23}	S_{33}	0	–	0	–

Figure 3: This table shows that 27 different combinations of switches are obtained using 9 bidirectional switches. Keeping in view the modulation constraints only 21 switching combinations are useful. The last three switching combinations provide zero vectors. The other six combinations are not useful because these combinations can not provide the reference vectors.

3 Modulation Techniques

The relations between input and output voltages are related to the states of the nine bidirectional switches with the condition that $0 < M_{ij} <1$ where $i, j = 1, 2, 3$. The variable M_{ij} represents the duty cycle of 9 bidirectional switches [31, 32]. The duty cycle must satisfy the following equations (32) (33) and (34).

$$M_{11} + M_{12} + M_{13} = 1 \tag{32}$$

$$M_{21} + M_{22} + M_{23} = 1 \tag{33}$$

$$M_{31} + M_{32} + M_{33} = 1 \tag{34}$$

Venturini proposed the method whose modulation function gives maximum value of voltage transfer ratio of 0.5 which is very low and is given by (35).

$$\begin{aligned} M_{ij} &= \frac{1}{3}\cos[b_o - (j-1)\frac{2\pi}{3}] \\ &+ \frac{2q}{3}[\cos a_o - (i-1)\frac{2\pi}{3}] \\ &* \cos[b_o - (j-1)\frac{2\pi}{3}] \end{aligned} \tag{35}$$

This method was modified by optimum method to increase the voltage transfer ratio to 0.866 and its modulation function is given by (36).

$$\begin{aligned} M_{ij} &= \frac{1}{3}\{1 + 2q[\cos b_h - (j-1)\frac{2\pi}{3}] \\ &* [\cos(a_o - (i-1)\frac{2\pi}{3}) \\ &- \frac{1}{6}\cos(3a_o) + (\frac{1}{2}\sqrt{3})\cos(3b_h)] \\ &- (\frac{2}{3}\sqrt{3})q\cos[(4b_h - (j-1)\frac{2\pi}{3}) \\ &- \cos(2b_h + (j-1)\frac{2\pi}{3})]\} \end{aligned} \tag{36}$$

4 Simulation and Results

Matlab/ Simulink is used for simulation and results. A complete step by step process is shown in a figure 4. A three phase source is required whose amplitude and frequency can be varied. Modulation block also modulates the switching intervals for the switches which in our simulation are insulated gate bipolar junction transistors (IGBTs).

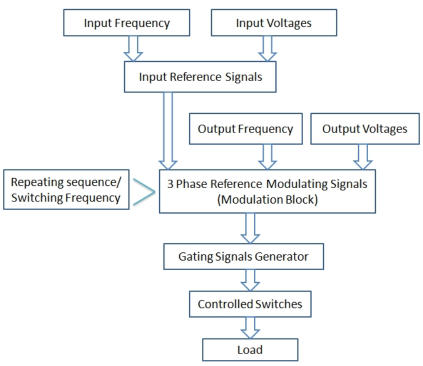

Figure 4: Flow Chart for the Implementation of PWM and SVM based Matrix Converters

The switching intervals are defined by using the solution as provided by the Venturini Method [31, 32]. Using Venturini method, two solutions are obtained. The first solution is given by (37).

$$M_1(t) = \tfrac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} + 2q$$

$$\begin{bmatrix} cos(\omega_m t) & cos(\omega_m t - \frac{2\pi}{3}) & cos(\omega_m t - \frac{4\pi}{3}) \\ cos(\omega_m t - \frac{4\pi}{3}) & cos(\omega_m t) & cos(\omega_m t - \frac{2\pi}{3}) \\ cos(\omega_m t - \frac{2\pi}{3}) & cos(\omega_m t - \frac{4\pi}{3}) & cos(\omega_m t) \end{bmatrix} \tag{37}$$

with $\omega_m = (\omega_0 - \omega_i)$. This yields $\phi i = \phi o$, i.e. the input phase displacement is the same as the load phase displacement. The alternative solution is given by (38).

$$M_2(t) = \tfrac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} + 2q$$

$$\begin{bmatrix} cos(\omega_m t) & cos(\omega_m t - \frac{2\pi}{3}) & cos(\omega_m t - \frac{4\pi}{3}) \\ cos(\omega_m t - \frac{2\pi}{3}) & cos(\omega_m t - \frac{4\pi}{3}) & cos(\omega_m t) \\ cos(\omega_m t - \frac{4\pi}{3}) & cos(\omega_m t) & cos(\omega_m t - \frac{2\pi}{3}) \end{bmatrix} \tag{38}$$

with $\omega_m = -(\omega_0 + \omega_i)$. This yields ϕ_i = - ϕ_o, i.e. the input phase displacement is the reverse of the load phase displacement. Combining the two solutions provides the means for input displacement factor control given by (39).

$$[M(t)] = \alpha_1[M_1(t)] + \alpha_2[M_2(t)] \tag{39}$$

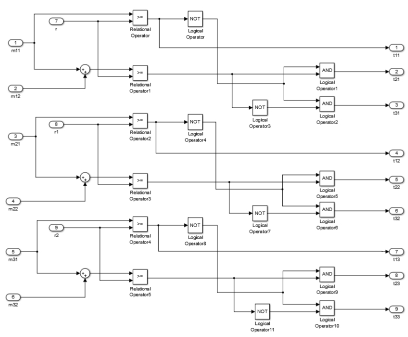

Figure 5: Gating Signal Generator

Combined solution allows input displacement factor control. This can be explained by taking the example of an inductive load. If:

- a1 = a2 : input is resistive (unity displacement factor)
- a1 > a2 : input is inductive (lagging displacement factor)
- a1 < a2 : input is capacitive (leading displacement factor)

The output voltages are thus produced by using these switching intervals and the input voltages.

Since, the transfer ratio is 0.5, so the output voltages cannot be increased by the half value of input voltages. Gating signal generator is shown in figure 5. The six signals of the switching intervals are compared with the repeating sequence taken as reference to produce the gate signals for the IGBTs. This is pulse width modulation. Matrix converter and space vector modulation based matrix converters are shown in figures 6 and 7 respectively.

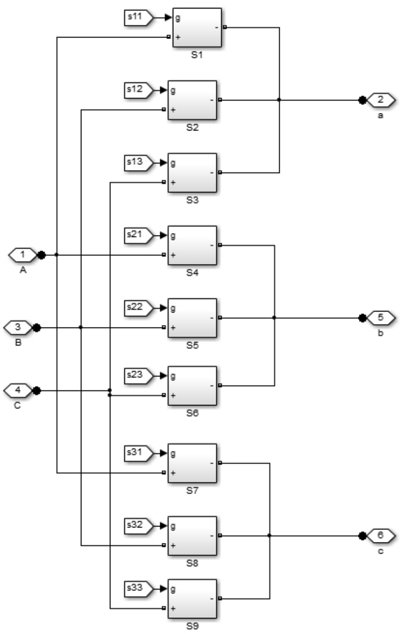

Figure 6: Matrix Converter

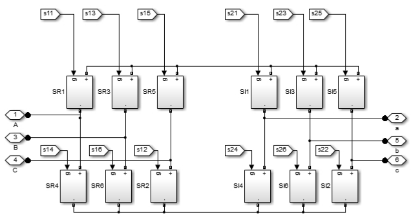

Figure 7: SVM based Matrix Converter

4.1 Case Studies

4.1.1 Test Case IA: Fixed Input Frequency and Variable Output Frequency

In the test case IA, input frequency is fixed and output frequency is varied. It is observed that change in output frequency does not affect the input frequency when PWM and SVM based AC to AC matrix converters are employed as shown in figures 10, 11 and 12.

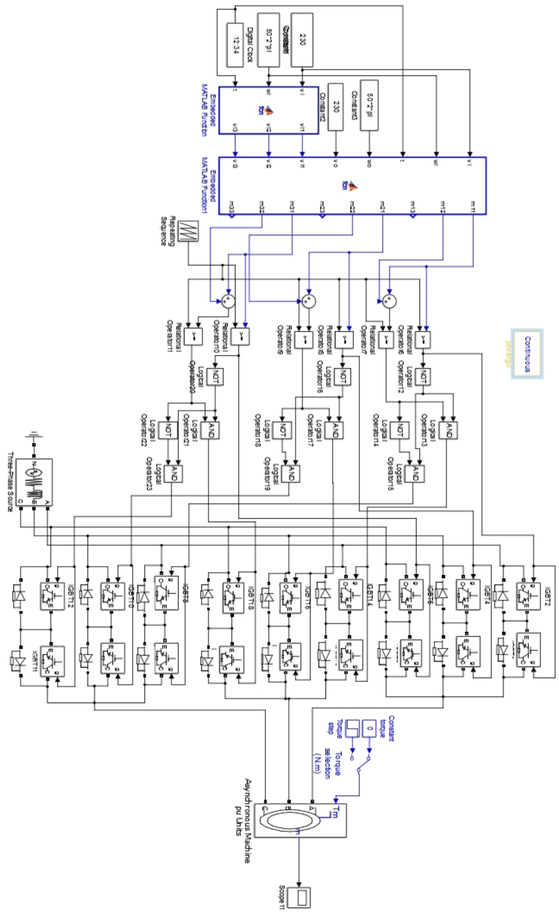

Figure 8: Circuit Diagram of PWM based Matrix Converter

4.1.2 Test Case IB: Variable Input Frequency and Fixed Output Frequency

In the test case IB, output frequency is fixed and input frequency is varied. It is observed that change in input frequency does not affect the output frequency when PWM and SVM based AC to AC matrix converters are employed as shown in figures 13, 14 and 15.

4.1.3 Test Case IIA: Fixed Input Voltage and Variable Output Voltage

In the test case IIIA, input voltage is fixed and output voltage is varied. It is observed that change in output voltage does not affect the input voltage when PWM and SVM based AC to AC matrix converters are employed as shown in figures 16, 17 and 18.

4.1.4 Test Case IIIB: Fixed Output Voltage and Variable Input Voltage

In the test case III, output voltage is fixed and input voltage is varied. It is observed that change in input voltage does not affect the output voltage when PWM and SVM based AC to AC matrix converters are employed as shown in figures 19, 20 and 21.

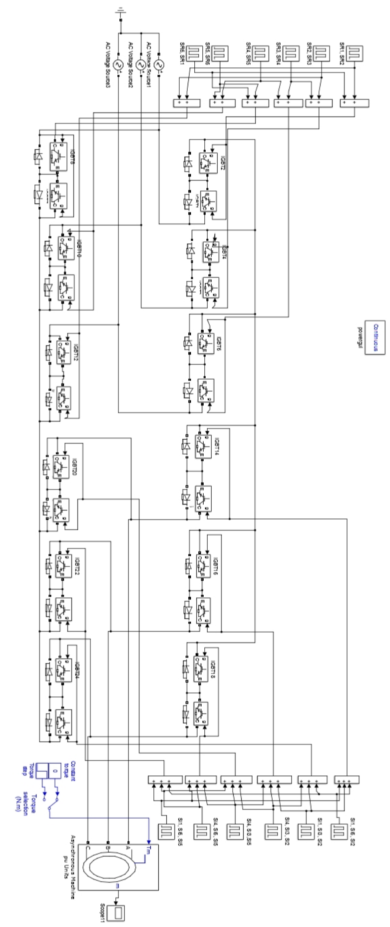

Figure 9: Circuit Diagram of SVM based Matrix Converter

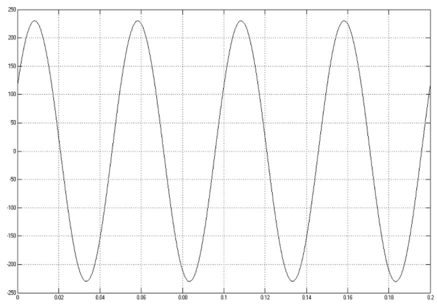

Figure 10: 20Hz Output Signal with 50Hz Input Signal Frequency.

4.1.5 Test Case III A: FFT Analysis for Pulse Width Modulation Based Matrix Converter with Fixed Input Frequency

Fast Fourier Transform Analysis for PWM based matrix converter is carried out as shown in figures 22, 23 and 24. It is found that this matrix converter maximizes the fundamental content of the characteristics by reducing the harmonic content. Any desired output frequency with maximum fundamental content can be obtained with this model by fixing the supply frequency.

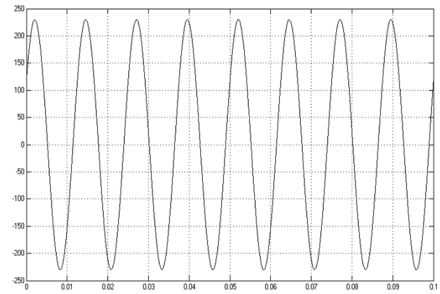

Figure 11: 80Hz Output Signal with 50Hz Input Signal Frequency.

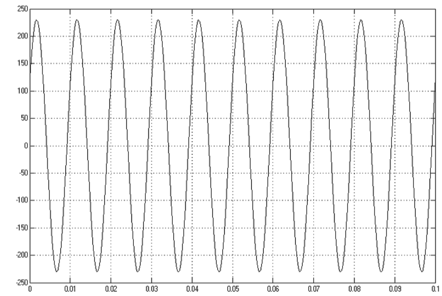

Figure 12: 100Hz Output Signal with 50Hz Input Signal Frequency.

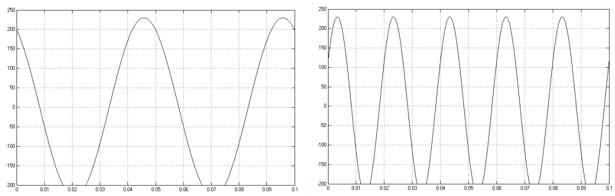

Figure 13: 20Hz Input Signal with 50Hz Output Signal Frequency.

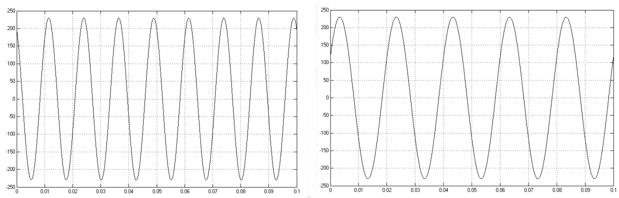

Figure 14: 80Hz Input Signal with 50Hz Output Signal Frequency.

4.1.6 Test Case III B: FFT Analysis for Pulse Width Modulation Based Matrix Converter with Fixed Output Frequency

Fast Fourier Transform Analysis for PWM based matrix converter is carried out as shown in figures 25, 26 and 27. It is found that this matrix converter maximizes the fundamental content of the characteristics by reducing the harmonic content. Any desired input frequency with maximum fundamental content can be supplied with this model by fixing the output

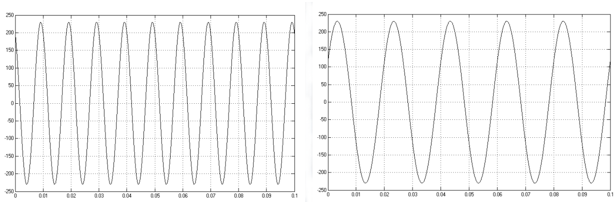

Figure 15: 100Hz Input Signal with 50Hz Output Signal Frequency.

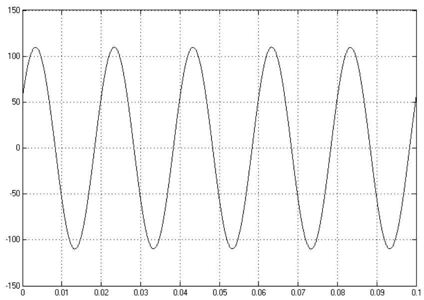

Figure 16: 110V Output Signal with 220V Input Signal Frequency.

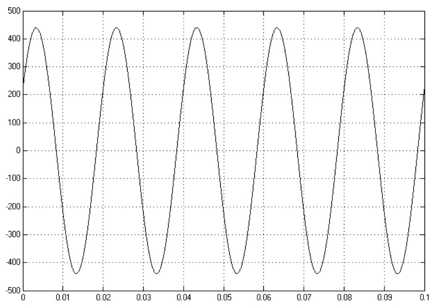

Figure 17: 440V Output Signal with 220V Input Signal Frequency.

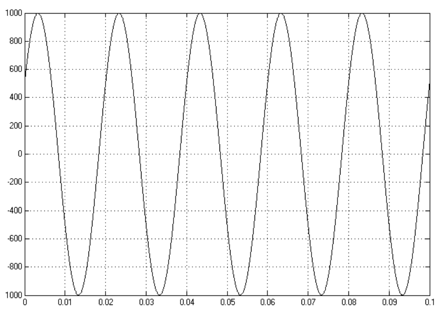

Figure 18: 1000V Output Signal with 220V Input Signal Frequency.

frequency or in other words, fixed frequency applications can work smoothly irrespective of the variation in the supply frequency by deploying this model.

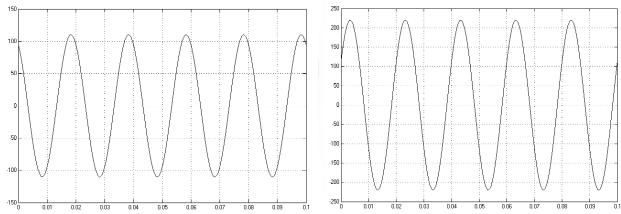

Figure 19: 110V Input Signal with 220V Output Signal Frequency.

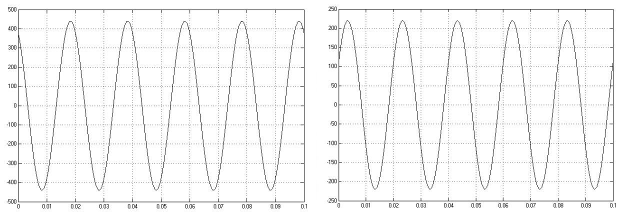

Figure 20: 440V Input Signal with 220V Input Signal Frequency.

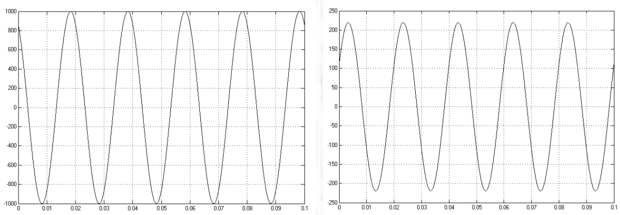

Figure 21: 1000V Output Signal with 220V Input Signal Frequency.

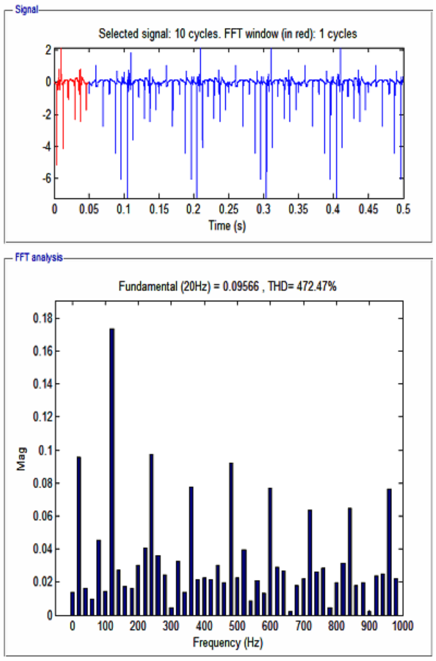

Figure 22: FFT analysis of 20Hz Output Signal with 50Hz Input Signal.

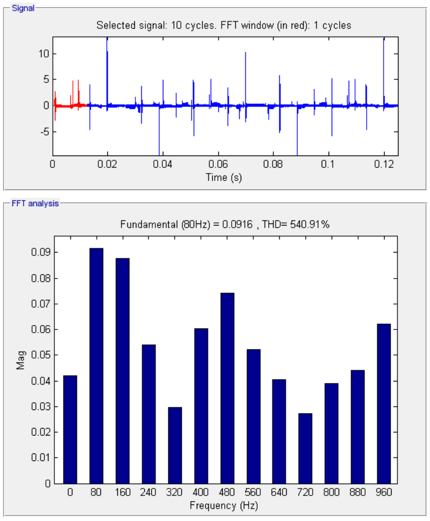

Figure 23: FFT analysis of 80Hz Output Signal with 50Hz Input Signal.

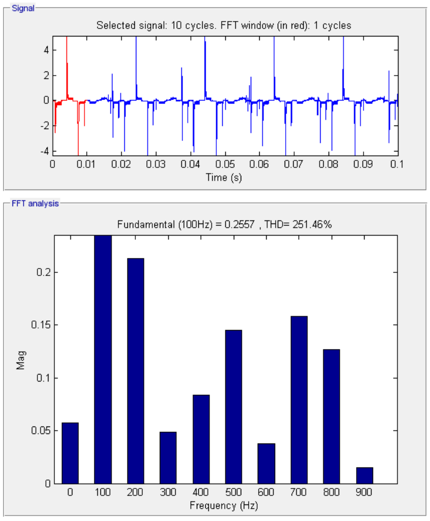

Figure 24: FFT analysis of 100Hz Output Signal with 50Hz Input Signal.

4.1.7 Test Case IV A: FFT Analysis for Space Vector Modulation Based Matrix Converter with Fixed Input Frequency

Fast Fourier Transform Analysis for SVM based matrix converter is carried out as shown in figures 28, 29 and 30. It is found that this matrix converter maximizes the fundamental content of the characteristics by reducing the harmonic content. Any desired output frequency with maximum fundamental content can be supplied with this model by fixing the input frequency. Total harmonic distortion is lower as compared to PWM based matrix converter.

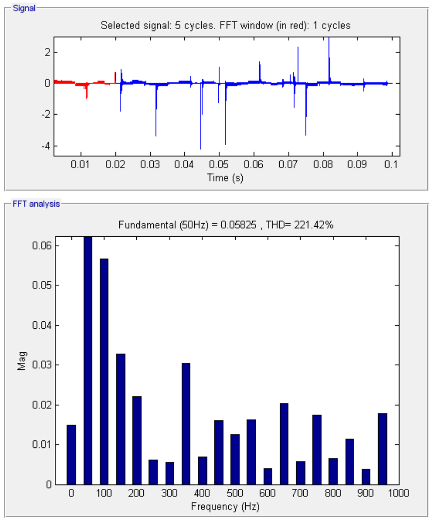

Figure 25: FFT analysis of Fixed Output 50Hz with 20Hz Input Signal.

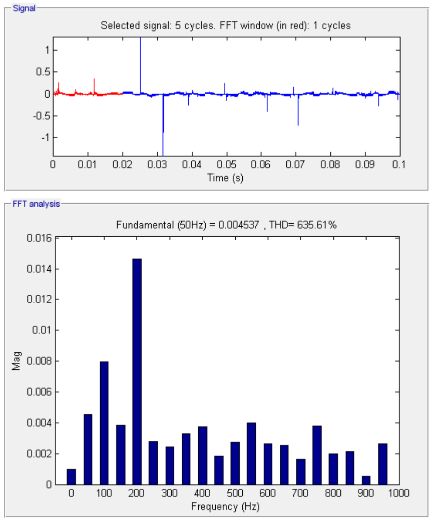

Figure 26: FFT analysis of Fixed Output 50Hz with 80Hz input Signal.

4.1.8 Test Case IV B: FFT Analysis for Space Vector Modulation with Fixed Output Frequency

Fast Fourier Transform Analysis for PWM based matrix converter is carried out as shown in figures 31, 32 and 33. It is found that this matrix converter maximizes the fundamental content of the characteristics by reducing the harmonic content. Any desired input frequency with maximum fundamental content can be supplied with this model by fixing the output frequency or in other words, fixed frequency applications can work smoothly irrespective of the variation in the supply frequency by deploying this model. Total harmonic distortion is lower as compared to PWM based matrix converter.

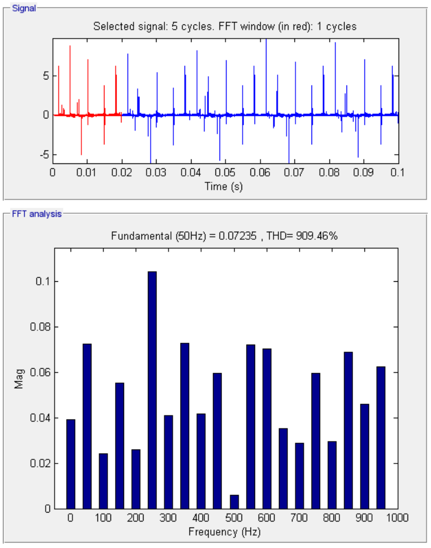

Figure 27: FFT analysis of Fixed Output 50Hz with 100Hz input Signal.

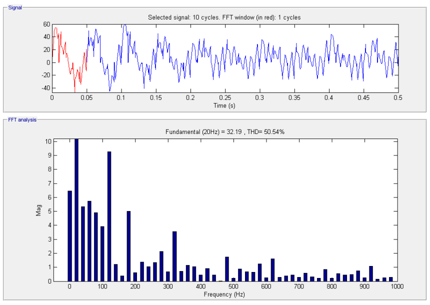

Figure 28: FFT analysis of 20Hz Output with 50Hz Input Signal.

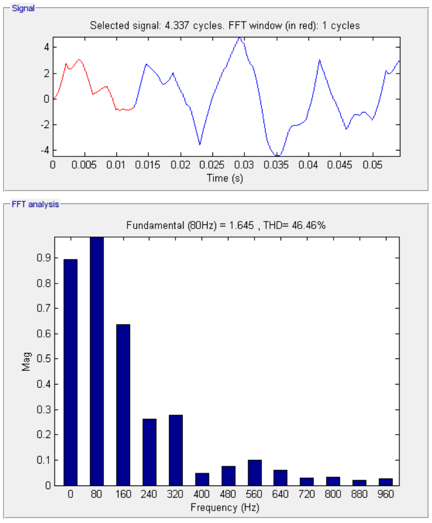

Figure 29: FFT analysis of 80Hz Output with 50Hz Input Signal.

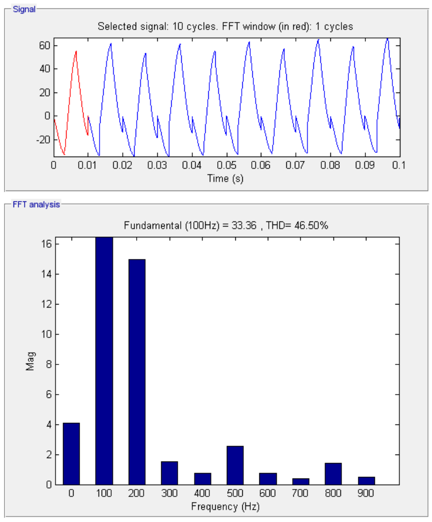

Figure 30: FFT analysis of 100Hz Output with 50Hz Input Signal.

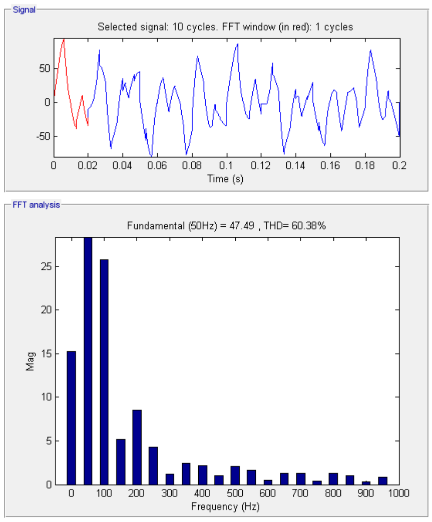

Figure 31: FFT analysis of output with 50Hz Output and 20Hz Input Signal.

5 Conclusion

In this research, PWM and SVM based three phase AC to Ac matrix converters are developed. Simulations are performed on Matlab. It is found out that PWM and SVM based matrix converter can be deployed to achieve any desired output and input characteristics. These converter are highly applicable for adjustable speed drives or variable frequency drives because in these proposed models it is shown that irrespective of any supply frequency, variable desired frequency can be attained. Secondly, this proposed model has revolutionized the applications requiring variable voltages. Any desired output voltage can be achieved without taking into consideration of input voltage and vice versa. Interconnected systems can be free of synchronization issues by employing these converters. Further, harmonic contents are greatly reduced and it has maximized the fundamental content of the desired characteristics. SVM based matrix converter offer low total harmonic distortion than PWM

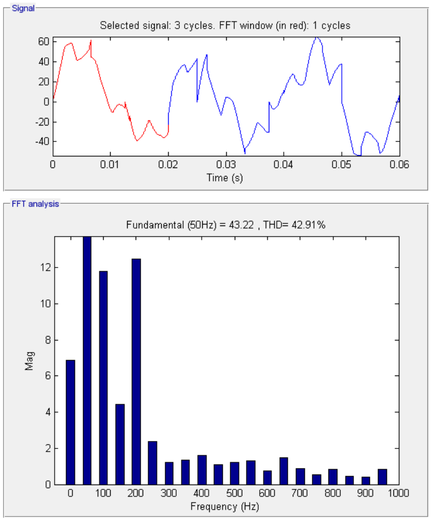

Figure 32: FFT analysis of output with 50Hz Output and 80Hz Input Signal.

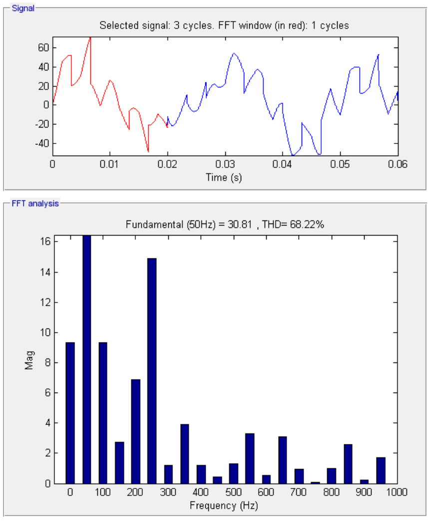

Figure 33: FFT analysis of output with 50Hz Output with 100Hz Input Signal.

based matrix converter.

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Biographies

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